Extension of the Test Coverage of the Automatic Band Switch Feature in the Low Layers of Mobile Phones

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Abstract

GSM is the basic protocol that was used in the first mobile phones. Although some new 3G protocols are more performing, GSM will remain the heart of mobile telephony history. The first part of this master thesis will present the development of telephony, of cellular telephony and of this protocol in particular. General aspects of the GSM specifications will then be described, gradually specializing in the issues of PLMN selection. Motorola's automatic bandswitch feature will then be explained, as well as its improvement, named EAB. The aim of this work being the testing of this feature, a theoretical description of testing methodology will first been shown, before the practical reasons concerning the choice of relevant tests are evoked.

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0 Index

This section lists the abbreviations used in this document.

AGCH: Access Grant CHannel
ARFCN: Absolute Radio Frequency Channel Number, number from 0 to 1023 representing a frequency.
BCCH: Broadcast Control CHannel
BSC: Base Station Controller, subpart of a BSS, controls a set of BTS.
BSS: Base Station Subsystem, part of the GSM architecture used for radio resource management
BTS: Base Transceiver Station, subpart of a BSS, first emitter-receiver linked to the MS.
CBCH: Cell Broadcast CHannel
EAB: Enhanced AutoBand feature, Motorola feature enabling to switch from the European to the American frequency bands and vice-versa
FACCH: Fast Associated Control CHannel
FCCH: Frequency Correction CHannel
FPLMN: Forbidden PLMN, a PLMN on which the MS is only allowed to camp on emergency
FSM: Finite State Machine, set of states linked by transitions, used to formalize a behavior
HLR: Home Location Register, subpart of a NSS, global database on users
HPLMN: Home PLMN, PLMN to which the user has subscribed
IMEI/IMSI: International Mobile Equipment/Subscriber Identity, to find a phone/subscriber in a network
KTH: Kungliga Tekniska Högskolan, great university
L1: Layer 1, physical layer in the MS architecture
LA: Location Area, group of adjacent cells
LAC: Location Area Code
LAI: Location Area Identifier, corresponds to the PLMN number (MCC and MNC) and the LAC
LRPLMN: Last Registered PLMN, see RPLMN
LU: Location Update, update of the location area of a MS
MCC: Mobile Country Code
MM: Mobility Management, one of the MS low protocol layers
MMI: Man Machine Interface
MNC: Mobile Network Code
MS: Mobile Station, a mobile phone with a SIM card
MSC: Mobile services Switching Center, subpart of a NSS, commutator.
MSISDN: Mobile Station ISDN number, the international phone number, known to the user
NSS: Network SubSystem, part of the GSM architecture used for call establishment and mobility
OSS: Operation SubSystem, part of the GSM architecture used by the operator to administrate the network
PCH: Paging CHannel
PLMN: Public Land Mobile Network, a network to which a user can subscribe to send and receive calls
PPLMN: Preferred PLMN, highest-priority PLMN after the HPLMN and RPLMN
RACH: Random Access CHannel
RPLMN: Registered PLMN, PLMN on which the MS is currently camped
RR: Radio Resource Management, one of the MS low protocol layers

SACCH: Slow Associated Control CHannel
SDCCH: Stand alone Dedicated Control CHannel
SCH: Synchronization CHannel
STEP: Simulator Tool for Early Protocol, simulator developed by Motorola to do tests on the low-protocol layers
TMSI: Temporary Mobile Station Identity, temporary number used to hide the IMSI
UIO: Unique Input-Output, a UIO sequence verifies a FSM is in a given state
VLR: Visitor Location Register, subpart of a NSS, local database often linked to a MSC

1 Introduction

1.1 Historical development of cell phones

"Mr. Watson -- come here -- I want to see you."

Such were the first words Alexander Graham Bell uttered to his assistant in 1876, in a device that could transmit messages electrically – called the telephone.

The patent for this revolutionary device was put down in 1870, by Elisha Gray, and Alexander Graham Bell, within hours. It was finally Graham Bell who was officially recognized as the creator of the phone, and who managed to perform such an incredible communication for the first time in 1876. This inventor wanted to create an evolution of the telegraph, by conjecturing that several messages could be transmitted at the same time on the same wire.

The telephone has gone through a very long way since 130 years, changing its look, ameliorating its performance, evolving along with society.

The beginning of wireless telephony occurred in the early 50's, when emitter-receiver devises were designed, using the 27 MHz band. These phones were influenced by the military Talky-Walky system, and could emit as far as 30 km. They used a lot of energy and were often installed in cars. Researchers discovered that it was possible to increase substantially the traffic capacity by using many small cells that would emit to some *cellular* phones. However, the required technology was not available yet.

At the beginning of the 70's, this system evolved in an automatic system, that became available to more (but still not many) people, but only in big cities.

In 1977, AT&T Bell produced the first cellular system prototype, which was tried for the first time one year later in Chicago. The first commercial cellular telephone was Japanese, in 1979. After Motorola and American Radio had achieved a second series of tests with another prototype in 1981, commercial cellular service was finally allowed in the USA.

During the 80's, most of today's big telecommunication companies developed and the telecommunication lobby structured.

So far, the first-generation mobiles were analogical. In 1991, GSM, which will be studied further, was designed and launched the second-generation wave of mobiles.

Today, third-generation cell phones are developed.

1.2 Cellular phone standards

1.2.1 Prehistory

A long, long time ago, in the 80's, was no global protocol to be found. Thy mobile phone could only emit to limited areas, and thee could certainly not communicate worldwide!

The Americans devised the AMPS protocol, which was tried in 1979 and commercialized in 1983. Thus the American people was able to communicate throughout the United States, although that was merely not possible between them and their Canadian neighbors, who invented AURORA-400 at the same time.

The Europeans, proud to be much less able to communicate between them than on the North-American mainland, designed various other protocols. It began well with Nordic Mobile Phone – NMT450 – that was used between Nordic and Benelux countries, and could have been an embryo of a unified European protocol. Alas, Great-Britain produced TACS (Total Access Communications System) four years later, soon followed by Germany with their C-NETZ, France with their Radiocom 2000, and Italy with their RTMI/RTMS. Eventually, Europeans had to cope with nine different, incompatible radio telephone systems.

Phone sales were naturally more significant in the USA than in Europe. Fortunately, the system that would enable Europeans to escape the consequences of this remake of the Babel tower scenario was developed step by step during the same years…

1.2.2 GSM history

The first essential condition to have a telephony service all over Europe is to define the same frequency band that will be used by everybody on the territory. That was done as soon as 1979, with the World Administrative Radio Conference, that opened the 900MHz band for mobile phones use.

In 1982, the European Conference of Posts and Telecommunications allocated the band from 890 to 915 MHz for the communications from the terminal to the network, and the band from 195 to 930 MHz for communications the other way. Simultaneously, the *Groupe Spécial Mobile* (GSM) was created, to specify a European communication protocol for 1990.

In 1985, after the project had developed slowly, the EEC decided to make the protocol designed by the GSM a protocol used by all member countries. In this group, France and Germany especially worked together.

In 1987, the phone operators in thirteen European countries signed an agreement to open simultaneously the GSM protocol in 1991. This agreement is called the Memorandum of Understanding (MOU).

But the technical specifications were only finished in March 1990. From there on, there was a considerable amount of work to perform, in hardware as well as software. The aim of the operators rapidly became to limit the lateness as much as possible…

In July 1991, the first communication between a mobile phone and a terminal was managed. In spite of many technical snags, the first networks opened by the end of 1991. Mobile phones broke through only a few years later.

As GSM networks opened throughout Europe, GSM lost its former French meaning to become *"Global System for Mobile communications"*.

Still in 1991, because of a British will, the GSM specifications were adapted to enable the development of systems in the 1800 MHz band. It is often called DCS 1800.

1.2.3 GSM today

ETSI stands for European Telecommunications Standards Institute. It is an independent company based in Sophia-Antipolis, near to Nice. In 1995, 350 members worked there. It includes people representing operators, industrials, administrations, researchers, and users, and they have the responsibility of the development and evolution of European standards.
GSM has now become the only numeric standard accepted in Europe, and is used in many countries. However, it is competing with other numeric standards, mainly in the USA and in Japan.

Today, the MOU had 210 members, spread over 105 different countries. Its aims are to promote GSM/DCS and to exchange information between the different protagonists involved in mobile communications.

In August 1998, there were more than 280 operational networks in the world and more than 100 million subscribers.

Last of all, GSM services are now available as well on bands 1900 MHz (PCS 1900) and 850 MHz (GSM 850).

2 GSM overview

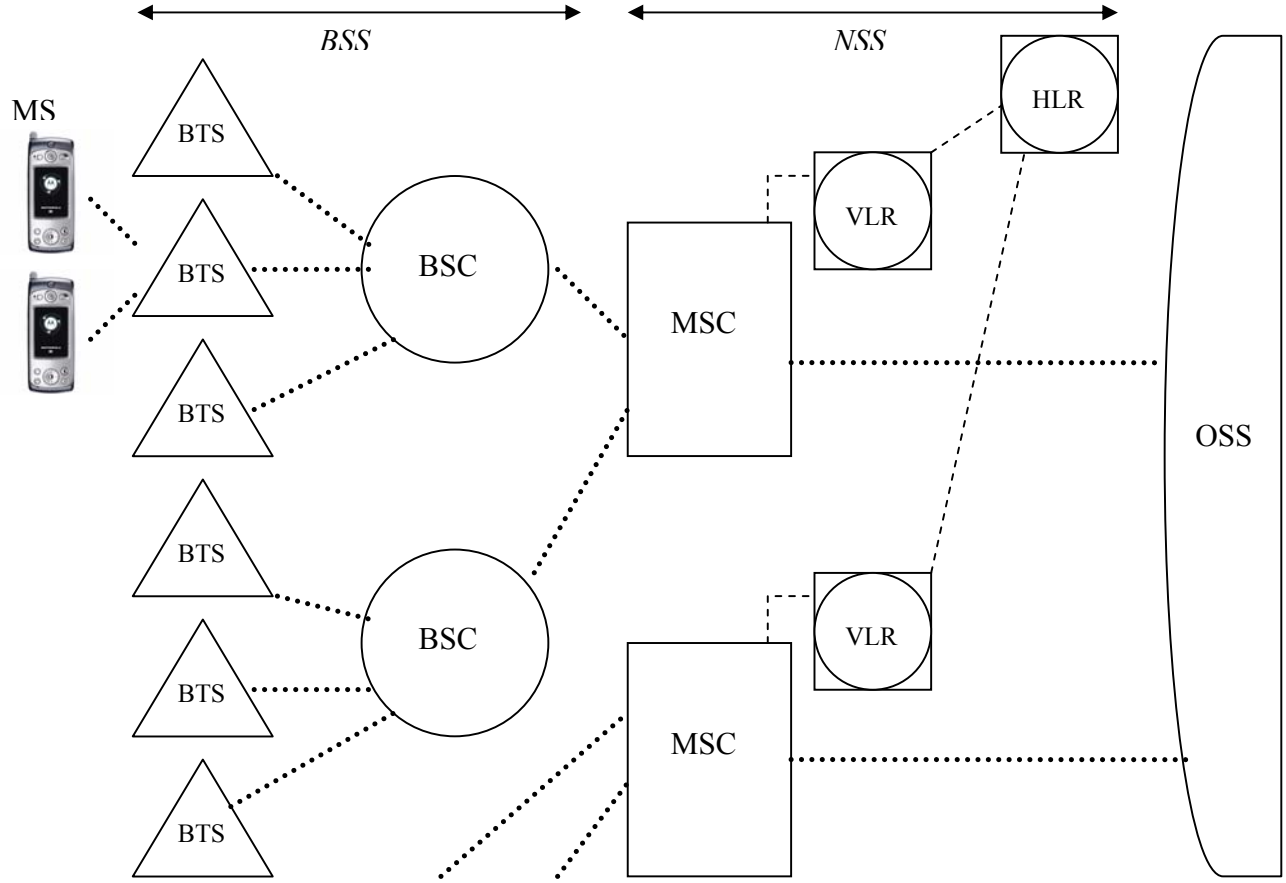
2.1 GSM architecture

2.1.1 Global architecture

A telephony network consists in four subsets of equipments:

* The Mobile Station (MS), which is the phone possessed by the user.
* The *Base Station Subsystem* (BSS), which manages radioelectric transmissions and radio resources. The handover, which is the possibility to move when calling someone, depends on the BSS.
* The *Network SubSystem* (NSS), which has all the functions needed for call establishment and mobility. It is sometimes also called SMSS, which stands for *Switching and Management SubSystem*. The itinerancy, which is the possibility to call anywhere – if there is coverage! – is linked to the NSS.
* The Operation SubSystem (OSS), which allows the operator to administrate its network.

Figure 1: GSM architecture



2.1.2 The MS

A mobile station designates a phone equipped with a SIM card, a device which allows having telecommunication services from a PLMN (*Private Land Mobile Network*, for example Orange).

There is a huge variety of phones, having always more functionalities, more battery autonomy and less volume and weight.

Each MS has a unique identity number called IMEI (*International Mobile Equipment Identity*) that also indicates the builder of the phone.

The maximal power for a MS is usually a few Watts.

2.1.3 The BSS

The BSS includes:

* Base Transceiver Stations (BTS), which are minimal emitting-receiving entities,
* Base Station Controllers (BSC), which control a set of BTS and have some higher functionalities.

2.1.3.1 The BTS

A BTS manages the radio transmission: modulation, demodulation, equalization, error correction coding. It looks at all the physical layer, and performs all the necessary measures to check a communication occurs normally. However, it releases the exploitation of these measures to the BSC.

A rural BTS can manage more than a hundred simultaneous communications, which is a limit seldom reached. A urban BTS can have more or less twenty simultaneous communications, but mini-BTSs are much more numerous in the cities or on the motorways.

A BTS covers from one to several square kilometers. Several BTSs are linked to a BSC, in chain or in star configuration.

2.1.3.2 The BSC

It is the intelligent part of the BSS. It allocates channels, uses the BTS measures to control the emission power of the MS and of the BTS, and performs handovers, which correspond to the possibility to move when talking on the phone.
It is also a commutator towards the MSC, which means it will relay information that has to be transferred to this more central element.

There are generally two ways of building BSCs:

* Numerous low-capacity BSCs for rural areas
* High-capacity BSCs for urban areas, where the BSC needs to coordinate many small BTSs.

2.1.4 The NSS

The NSS includes three kinds of components:

- The *Mobile services Switching Center* (MSC), which are mobile commutators usually associated with VLR databases
- The *Visitor Location Register* (VLR), which is a local database
- The *Home Location Register* (HLR), which is a user localization and characterization database.

2.1.4.1 The HLR

The HLR is a database that manages the subscribers of a given PLMN. For each subscriber, it also memorizes data that changes little with time:

- The *International Mobile Subscriber Identity* (IMSI), inside the network
- The *Mobile Station ISDN number* (MSISDN), which is the international phone number, known to the user
- The subscription profile.

The HLR memorizes the localization of the user (the user's VLR, see infra), and this is updated through information transmitted on the network.

The HLR can be designed in a centralized or decentralized way. In the first case, it is a specific machine containing hundreds of thousands of subscribers. In the second case, it can be integrated directly in the MSCs, where the data of a given user is stored in the MSC on which the user communicates most. The only important rule is that each user is assigned a unique HLR.

2.1.4.2 The VLR

A VLR memorizes the same data as a HLR, but only for subscribers inside a specific zone. It also stores the TMSI (*Temporary Mobile Station Identity*), which is a temporary number whose aim is to hide the IMSI.

2.1.4.3 The MSC

The MSC is a kind of nervous center for mobile communications. It manages the call establishment between the phone and another MSC, the transmission of short messages, and the handover in case the user is moving through different areas when calling.

The MSC communicates with its VLR to get all necessary information on its users.

A MSC can become a Gateway MSC, which is activated at the beginning of a call from a non-mobile to a mobile phone.

In the theory, MSCs and VLRs should be physically separated. Practically, the VLR is often integrated in the MSC, for matters of convenience.

2.1.5 The OSS

The OSS contains many parts: for example the Telecommunications Management Network (TMN), the Equipment Identity Register (EIR), and the AUthentication Center (AUC).

Its main roles are:

- Commercial administration (declaration of the subscribers, terminals, bills, statistics)
- Security management (intrusion detection, rights)
- Exploitation and performance management (traffic and quality observation, configuration changes to adapt to the network load, surveillance of mobiles)
- Control of the system configuration (software update, introduction of new equipments and functionalities)
- Maintenance (flaws detection, equipment tests).

2.2 Itinerancy management: roaming and handover

2.2.1 Cells and location areas

A cell is the area where a BTS has coverage. In a cell, it is possible for a MS to make calls by communicating with this BTS.

To be able to move from cell to cell, a simple method was used in the past: when you went out of the current cell, the network simply asked all cells where the phone was last seen. But this is quite wasteful, and can only be used for small populations.

A better idea is to introduce the concept of *location areas* (LA). A LA groups some adjacent cells together (from a few to 20 or 30). When the network needs to know where a user is when he/she has gone out of a cell, the system looks in the current LA, which will emit some paging messages to find the phone.

To use this method, the network must keep in mind the address of the current location area of the MS. A LA is identified by three numbers: MCC, which indicates the country of the PLMN; MNC, which indicates the number of the PLMN inside the country; and the LAC, which is the number of the LA. These 3 numbers constitute a LAI (LA Identifier).

Once the LA is found, a cell is defined by its frequency, represented by the ARFCN number. It also has a color code, to differentiate it from possible cells that could both be near and have the same frequency.

2.2.2 Local roaming

Local roaming corresponds to the situation when the user is moving from one location area to another. A location update is needed. This can only happen when the mobile is in idle mode, i.e. it is not performing a call (this would be dedicated mode).

Within GSM, there exists such a *location update* (LU) procedure. The decision to perform it comes from the mobile, which searches the current LAC and compares it to the stored value. It happens every $6N^{th}$ minute, N being an integer.

Globally, there are two kinds of scenarios: whether the LU occurs inside the same VLR or not. There is a common process before, though.

2.2.2.1 Common process to all scenarios

The MS is in idle mode. It detects some information indicating a new LA. To start the LU, the phone requests a dedicated channel from the network, i.e. a channel that is not used by any other user. Then, the MS establishes some connections in order to be able to communicate with the MSC managing the cell where the MS is located.

2.2.2.2 Intra-VLR location update

This is the easiest case. The LU information must only be modified in the VLR. The network can authenticate the mobile, allocate a new TMSI or keep the same.
Typically, this takes 300 ms.

2.2.2.3 Inter-VLR location update

Let us the call VLR1 the origin VLR, and VLR2 the destination VLR.

VLR2 does not know the TMSI of the phone. Hence, the mobile indicates also the whole LAI of its former LA. Then VLR2 is able to communicate with VLR1. VLR2 copies all the information

concerning the user, from the HLR whose address has been given by VLR1. VLR2 does not copy immediately from VLR1 to avoid error transmission. Once this is done, VLR1 erases its information on the user. A new TMSI is reallocated.

The IMSI may be used instead of the TMSI, in some special circumstances like on power-up, when a TMSI has not yet been allocated.

This procedure is slower and takes 5s.

2.2.3 International roaming

Each subscriber has a Home PLMN (HPLMN). But when he/she leaves the HPLMN coverage and is under coverage of another Visited PLMN (VPLMN), the MS may camp on the VPLMN (if some agreement with the HPLMN exists), and this is called international roaming.

The location update follows roughly the same outlines as for the previous exceptions. However, the MSC in VPLMN cannot communicate directly with the subscriber's VLR. It must make use of the HPLMN network, the VPLMN network, and the international network.

The protocol messages aspects and the different possible situations will be developed later, since this corresponds to the main theme of this master thesis.

2.2.4 Handover

A *handover* corresponds to the allocation of another dedicated channel to the MS when it is already in dedicated mode, i.e. when it is having a call.
There are two kinds of very different handovers: intra-cellular or inter-cellular.

2.2.4.1 Intra-cell handover

When the quality of the received signal becomes poor, at the same time the emitted power in the cell is high, it means that the problem may come from interferences in the current channel. Intra-cell handover then corresponds to the commutation of the call to another channel inside the same cell.

2.2.4.2 Inter-cell handover

An inter-cell handover happens when the signal quality would become better in a new cell. Typically, it can happen when you are calling someone in the street, and you continue walking until the power of the cell where the call was originated becomes too low.

An other possible cause of inter-cell handover is when there is too much traffic on a cell, the call is then redirected towards a neighboring cell less used.

2.2.4.3 Main phases in a handover

During a handover, the following operations are performed:

- Suspension of all normal operations except the radio resources (RR) management layer,
- Disconnection of the signalization link, and possibly of the traffic channel,
- Disconnection, deactivation and freeing of formerly allocated channels,
- Activation of new channels and connection if necessary,
- Establishment of a data link connection on the new channels.

2.3 The logical channels

2.3.1 Bursts

A burst is the basic element of data transmission in GSM. It has a length of 156.25 bits, which are successively sent. There are four kinds of non-dummy bursts:

- The normal burst (N), which is used to carry data and most signaling,
- The frequency burst (F), whose aim is to be synchronized in frequency with the cell signal,
- The synchronization burst (S), whose aim is to be synchronized in time with the cell signal,
- The access burst (A), which is a shorter version of the normal burst and is used to request channel allocation.

A burst is also called a time slot, and lasts 0.577 ms.

2.3.2 Frame, multiframe, superframe, hyperframe

From the time slots, several layers of information structures are built:

* A frame corresponds to 8 time slots, and lasts 4.615 ms,
* A multiframe is either a set of 26 frames (120 ms), or a set of 51 frames (235.4 ms),
* A superframe is either 51 26-multiframes or 26 51-multiframes. It lasts 6.12 s,
* A hyperframe corresponds to 2048 successive superframes, for a total time of 3h 28mn 53s 760ms.

2.3.3 Channels

These structures enable us to transmit information. But it would be wasteful to use a whole multiframe, for example, only for one kind of information. So, we need to define different types of logical channels. A logical channel is assigned a specified set of slots on a multiframe, and will read its information there. Then each slot of a multiframe will have a specific function.

There exist two groups of logical channels: signaling channels and traffic channels. At a given time, different associations of these channels are possible, depending on the needs.

2.3.3.1 Signaling channels

- *Frequency Correction CHannel* (FCCH): synchronizes frequency with a base station to be able to communicate with it.
- *Synchronization CHannel* (SCH): synchronizes time with a base station to be able to communicate with it; it is used at the same time as FCCH.
- *Broadcast Control CHannel* (BCCH): broadcasts regularly information in each cell, to be listened to by all the mobile stations in idle mode. It exists only in downlink transmission.
- *Paging CHannel* (PCH): it is used by the network to page the MS, the network broadcasts information in order to perform a call, send a SMS or authenticate.
- *Access Grant CHannel* (AGCH): it is used by the network to inform an idle MS it has to switch to a dedicated channel.
- *Random Access CHannel* (RACH): allows any MS to transmit its access request to the network. The MS may do so at a random time.
- *Cell Broadcast CHannel* (CBCH): in the cells where it is implemented, allows transmitting short messages from the network to all MSs in idle mode.
- *Slow Associated Control CHannel* (SACCH): transports signaling data in parallel with the transmission of a user data flow. It is associated to a traffic channel.
- *Fast Associated Control CHannel* (FACCH): as SACCH may be too slow, it may be preferable to use FACCH, which will avoid delay. But it is not transmitted periodically as SACCH.
- *Stand alone Dedicated Control CHannel* (SDCCH): dedicated channel that allows transmitting control data at a high rate.

2.3.3.2 Traffic channels

Traffic CHannels (TCH) are dedicated channels used to transmit coded speech and data. There are several kinds of TCHs, depending on the desired rate and on whether speech (at full- or half-rate) or data is transmitted.

3 The process of PLMN selection seen from the low protocol layers

3.1 L1, RR and MM protocol layers

L1, RR and MM are the names of the protocols layers on which my master thesis takes place. They are low protocol layers, which are described in the following paragraphs, from lowest to highest.

3.1.1 L1

L1 stands for *Layer 1*. It is the physical layer, which communicates directly with the receiving/emitting part of the system.

3.1.2 RR

RR is the *Radio Resource management* layer. Its main role is to establish a dedicated channel, or to reestablish it after a handover.

3.1.3 MM

MM, or *Mobility Management*, is a layer whose main roles are:

- To manage mobility, that is update the location through communication between the MS and the network,
- Insure security functions,
- Manage MM connections, which are a way to connect directly without mobility issues.

The main function that will be developed further is the first one, since it contains all the problems of PLMN selection and reselection.

3.2 When should we choose a new PLMN?

This Master Thesis handles a specific aspect (described in 4.) of all problems linked to PLMN selection and reselection. We will now describe all the situations when this event may happen.

3.2.1 Power-up

When the phone is switched on, it needs to register as soon as possible on a new PLMN. But it will be possible to send calls only if a SIM card is inserted (and if an available PLMN is found, of course!). If the last PLMN on which the MS was registered is found, the MS will register on this one.

3.2.2 Loss of camp

We may lose the connection to the current PLMN in several situations: for example, you are in a car and you drive into a tunnel; or you simply walk out of the coverage area of your provider.

In this situation, the phone will try first to recamp (i.e. reconnect) on the same PLMN. If it is not possible, it will try to connect on other PLMNs.

3.2.3 Network registration failures

If the phone cannot update its location four times in a row, communicating would be useless, and a special procedure is engaged as a consequence. The MS tries to camp on a new available PLMN.

3.2.4 Periodic HPLMN scan

Every $6N^{th}$ minute, where N is an integer, the phone performs a home PLMN search if it is not already camped on its home PLMN – i.e. the PLMN for which the user has subscribed. If the home PLMN is found, the MS leaves the last PLMN to camp on this one.

3.2.5 Manual network search or new network search

At any time, the user may request a manual network search. The result is a PLMN list appearing on the screen, and the user will have to choose the PLMN that he wants to use.

Motorola has also developed the “New Network” option, which tells the phone to camp on a PLMN other than the PLMN being currently camped on.

3.3 Particular PLMNs

For the following sections, it is important to distinguish between the different possible attributes of a PLMN, and to remember the abbreviations used. Here is a list presenting the different specific PLMNs that will be used.

3.3.1 Registered PLMN

The *Registered PLMN*, or RPLMN, is the PLMN on which the MS is currently camped. When searching a PLMN (for example if the phone loses track of the RPLMN), the RPLMN will nearly always have highest priority.

Another abbreviation that can be used is LRPLMN, which stands for Last Registered PLMN. It intervenes for example at power-up, when the phone remembers it was last camped on this PLMN.

3.3.2 Home PLMN

The *Home PLMN*, or HPLMN, is the PLMN for which the user has subscribed. If the phone is allowed to camp on PLMNs other than the HPLMN, it is because the HPLMN has made commercial agreements with those other PLMNs.

When the RPLMN cannot be found, the HPLMN is chosen. The exception is for the periodic HPLMN search, when the HPLMN has a higher priority than the RPLMN.

3.3.3 Preferred PLMNs

A MS may have a list of *Preferred PLMNs*, or PPLMNs. A PPLMN will be chosen first if neither the (L)RPLMN nor the HPLMN can be found.

If several PPLMNs are mentioned, they are sorted by order of decreasing preference.

3.3.4 Forbidden PLMNs

A *Forbidden PLMN*, or FPLMN, is a PLMN on which it is forbidden to camp for the phone.

At power-up, the FPLMN list is empty, and is filled up after each failed attempt to camp on a PLMN. Assume a given user has subscribed for Orange. At power-up, SFR and Orange cells are found. The phone tries to camp on a SFR cell, but is rejected. As a consequence, SFR is added to the list of FPLMNs (until next power-down).

If no suitable PLMN is found at a given time, and if only FPLMNs are available, then the phone will not camp normally, but will camp on emergency instead. That means the MS will camp on a FPLMN cell, but will only be able to launch emergency calls. In this state, the MS will only receive information from the network and will not be able to perform any call. However, calling emergency numbers such as the police or the fire brigade remains possible.

4 The Enhanced AutoBand feature

This is the feature for which tests had to be designed during my Master Thesis. The feature will be abbreviated as EAB.

4.1 European and American frequency bands

4.1.1 List of frequency bands

Basically, GSM was only designed to be used in the 900 MHz frequencies (GSM900), which were made available by some European governments. The United Kingdom rather used the 1800 MHz frequencies, which were then added to the GSM capability (DCS1800). Some enlargements of the band width of GSM 900 were performed, distinguishing EGSM (Extended GSM) from PGSM (Primary GSM). In the following, the combination of both will be referred to as GSM900.

900 and 1800 are the European frequency bands. Before the introduction and the treatment of the American bands, the most performing phones in terms of frequency coverage were thus dual-band phones, with coverage 900/1800.

But the USA had decided to use other frequency bands, surrounding 1900 and 850 MHz. So, GSM had to adapt, and PCS1900 appeared, soon followed by GSM850. From there on, Motorola has tried to offer new services, with tri- or quad-band, covering European and American bands. But adding the 850 and/or 1900 capability to phones is much less easy than adding 1800 to 900, for example because there can be frequency overlapping between some bands.

4.1.2 Regional presence of frequency bands

The following map shows the geographic repartition of the frequency bands used by the operators in the different countries of the world.

We can divide the world into two large regions: America and the rest.

In Europe, Asia, Africa, Australia, and in the Pacific, the European bands 900 and 1800 are used. However there are a few exceptions, in which:

- Thailand, which also has a 1900 network (and 3G, though it is not indicated on the map)
- Japan and South Korea, where the coverage is only 3G.

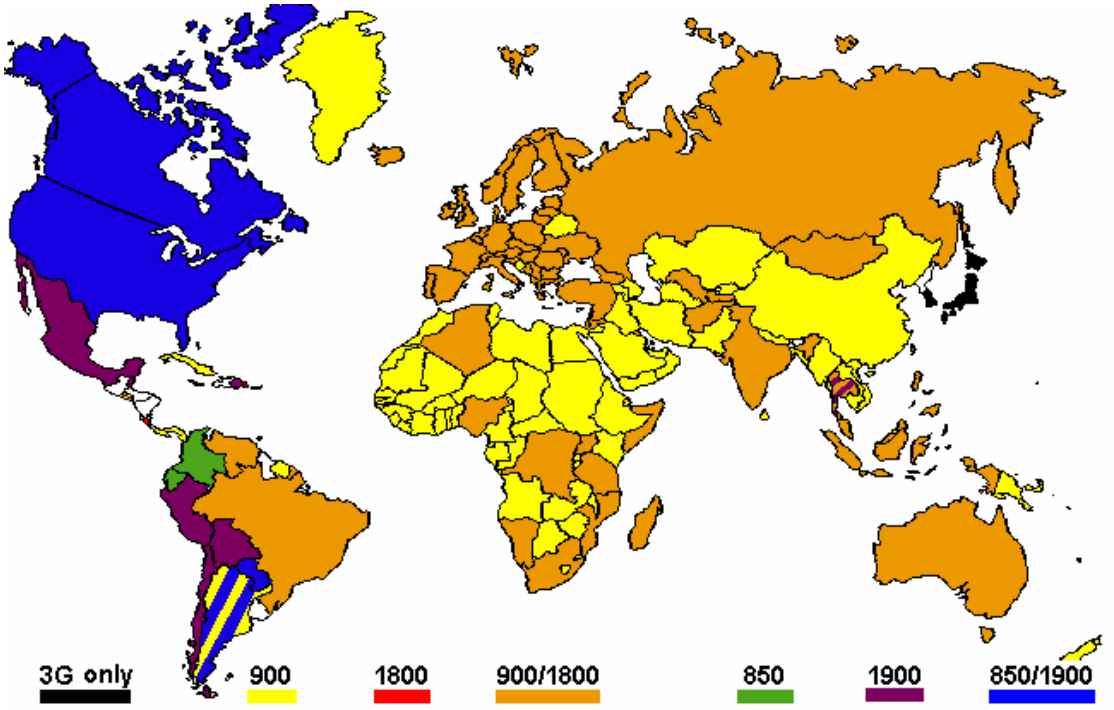


Figure 2: Frequency bands used in the world

It is remarkable that Europe is the most homogenous region, where all countries except Belarus (only 900), have a coverage on both 900 and 1800.

The largest variety of frequency bands appears in America. Both American bands, i.e. 850/1900, can be found in the USA, in Canada and in Paraguay. Other countries only have coverage on 850, like Colombia, or on 1900, like Mexico.

But some American countries have European bands instead, like Cuba (probably as a desired contrast to the USA!). Argentina is the only American country to have some coverage on both European and American bands, i.e. on 900 and 850/1900.

No country in the world has coverage only on the 1800 band (though Brazil is not far from it).

The main conclusion of this map is that it is unavoidable to develop telephones that can switch from the European to the American bands, and vice-versa, and particularly for countries like Thailand or Argentina.

4.1.3 ARFCN and induced problem

An international agreement created the ARFCN, which stands for *Absolute Radio Frequency Channel Number*.

Each cell has an ARFCN number, which represents a given frequency. It is ranged between 0 and 1023.

With dual-band phones on 900/1800, it was guaranteed this number corresponded to a unique frequency. Unfortunately, it became more complex with the introduction of the 850 and 1900 bands. As a matter of fact, there is a large overlapping between DCS1800 and PCS1900:

- ARFCN for DCS1800 range from 512 to 885,
- ARFCN for PCS1900 range from 512 to 810.

This issue contributes to the complexity of the automatic band switch feature, which offers a way to handle the problem.

4.2 Basic Autoband

4.2.1 Automatic band switch

Automatic band switch, autoband in short, is a feature that permits to perform calls with the same MS, in countries where the coverage is 900/1800 or in countries where the coverage is 850/1900.

At power-up, the MS scans the usual frequency band to find its RPLMN or HPLMN. If it finds no coverage, it treats the possibility that we are in another country, supporting other frequency bands.

The MS then searches on the other possible frequencies.

4.2.2 When can it be used?

This feature is useful for people living near to the border of two differently covered countries, like between Chili and Brazil. It can also be used when people travel from Europe to the USA for example, and avoids buying another phone that would cover the other frequency bands.

4.2.3 Limitations

Since the time of the original design of the Autoband feature, there is now at least one country that has coverage on both European and American frequencies.

Today, Thailand is an example of such a country. While in Bangkok, TOT provides a 1900 coverage, the rest of the country has a 900/1800 coverage with AIS. As a consequence, someone that powered on his/her phone in the capital city will not be able to call anybody once he/she has left the town! In the same way, a person coming from the countryside with the MS switched on will have no coverage in Bangkok!

This is not the only limitation. The same problem occurs for the previously mentioned people at the border of Chili and Brazil. If they want to eat a taco on the other side of the border, their phones will not be able to recognize the frequency bands, unless they switch off their phone, and switch it on again.

4.3 Enhanced AutoBand

Enhanced AutoBand, EAB in short, is an improvement of the previously described feature whose aim is to palliate its limitations.

With the EAB, it is possible to look on both European and American bands, not only at power-up, but anytime when a PLMN reselection process intervenes. The consequence is the possibility to travel anywhere without ever switching the phone off!

However, a user may wish to stay only on European bands or on American bands. The reason may be quickness matters, or energy saving. To do this, a network option on the phone allows the user to choose between Autoband, 900/1800 or 850/1900.

The EAB algorithm involves several software components of the phone from low layers of GSM protocol to MMI. It introduces several new concepts, algorithms and variables that have to be thoroughly analyzed before attempting to test them.

5 Testing a communication protocol

Communication protocols, such as GSM, are very complex. One way or another, we have to perform tests to avoid the inevitable bugs that would occur if we did nothing. This section presents the use of formal methods to do tests. In a first part, the interest of formalization is shown. The basics of formal testing are then presented, before an example of a formal method – *Finite State Machines* (FSMs) – is developed in the last part.

5.1 Why use formal methods?

5.1.1 A history of automated validation

The first automated validation attempt goes back to 1970. At this time, the perturbation (or reachability) concept was introduced. It consists, for a given state of the system, in deriving all the possible successor states, and continuing recursively until all states have been reached. The involved researchers then discovered that it was possible to reveal design errors even in simple protocols, that would have been very difficult to detect had the analysis been made manually. However, they had no high-level notation in 1970 and the verification was tricky.

In 1980, automatic proofs still required a great deal of work. For each new specification problem, most of the verification code had to be rewritten. The automatic validation was still far from being a method accessible to the engineer.

Later, special-purpose languages were a breakthrough. They could be used to specify the validation system's input. The consequence was the possibility to directly use the perturbation analysis from the output of a parser run on a formal specification. But there were still major limitations, such as the difficulty to analyze the origin of inconsistencies.

Today, it is possible to map machine states to specifications states much more efficiently. High-level specification languages are at our disposal, such as *Promela*. There is near certainty that the regular use of such a language could make us detect errors in the protocols specifications of the last ten years! However, the use of formal testing is still not widely known, although it is ready to bring much to the industrial companies that could need it.

5.1.2 The advantages of formal design

In a traditional design cycle, we can distinguish three main steps:

1 – High-level design, when the global design is thought according to the requirements
2 – Low-level design, when designers further detail the solution found in step 1
3 – Coding and testing, when the code is divided between the programmers to be implemented

Today, in industrial companies, and especially in Motorola, most of the time is spent on the third phase. Since there is no formal verification for high- and low-level design, coding is the first step in the process when the engineers have to face a formal, unambiguous language, which is here the programming language.

The consequence of this is that too much time is spent on debugging the implemented code, a problem that could have been avoided if we had used a formal method to check the validity of the design during a previous step. Furthermore, when debugging in step 3, we often have to go back to the low-layer design, or even sometimes to the high-level design, which is a pure waste of energy.

Hence, the solution is to use formal verification softwares, with whom it will be possible to formally validate the design levels, and be assured that the debugging phase will be minimal since it will not be based on an inconsistent design.

5.2 Formal methods

5.2.1 Design criteria

A formal method needs to use:

- Unambiguous notations
- An effective validation tool that will check the logical consistency of high-level specifications.

Three kinds of criteria have to be used to check the correctness of a protocol:

- General logical correctness criteria, they do not depend on the type of protocol that is being tested. This category groups all common errors such as deadlocks, unspecified receptions, or buffer overflow.
- Protocol-specific correctness criteria. For GSM, such a criterion could be: *"MM must receive a REG_REQ primitive at power-up"*.
- Real-time performance requirements. This can correspond to a limited time for call establishment, for example.

The first two types of criteria aim at avoiding underspecification – we reach a state where we do not know what to do – or overspecification – some code is never reached. The third criterion necessitates a methodology different from the other two, and it will not be detailed further.

5.2.2 Formal languages

5.2.2.1 Single and dual languages

Two aspects have to be tested: the specifications, and the requirements, that correspond to the first two types of design criteria. Depending on what we are looking for, we can use a single language or a dual language.

If we use a single language, only the specifications are translated, and the requirements are not. The aim is to transform step by step a simple high-level design into a more detailed design by proving the successive equivalences.

If we use a dual language, we have different formal notations for the specifications and for the requirements. The proof method is independent from the protocol, and more effective.

We will now look in further detail into the dual language choice, which is the most realistic one if we want to be able to adapt quickly to any kind of problem.

5.2.2.2 Behavior and specifications requirements

Different languages have to be used for the specifications and for the requirements, because they do not express the same things. Whereas the specifications describe *how* the system works, the requirements tell *what result* we await from the system.

There are many ways to formalize the specifications. Among the most used, we can quote the extended finite state machines (see 5.3) and full-fledged programming languages.

On the other hand, the requirements are very often formalized using temporal logic. However, one given formalization cannot cover all the cases, and we need to choose the best subset of criteria for which it will be possible to perform a formal verification.

5.2.3 Validation methods

Validation is the step when the previous formalizations are used, to check the requirements are fulfilled in the given specification.

As the specifications grow more complex, we have to face a problem of states explosion. To compensate for this, we can try to have more powerful machines (that's already the case!) and techniques. Here are three examples of improvements that have been brought to validation algorithms.

5.2.3.1 On-the-fly verification

Earlier, multi-pass algorithms were used. But all states needed to be created before the verification could really begin. This is near to impossible in some problems where only samples of the states set can be studied simultaneously. On-the-fly-verification ameliorates this, because the states are not all created before. Breadth-first or depth-first methods can be used, but the latter one is the best one.

5.2.3.2 State-space compaction

This method is faster than the previous one, but there is a low probability that some states will not be covered. However, the better efficiency of state-space compaction allows it to be used for industrial problems. In this method, we use a hash function for the different states. The hash table has a limited size, and finding a state that has an already used hash value stops the search of the branches coming from this state. The state coverage depends on the ratio of the memory used for the hash table over the memory used for the states.

5.2.3.3 Partial-order semantics

They reduce the number of interleavings (i.e. the choices of action in a given state) that have to be explored. As a matter of fact, it is usually very difficult to find if two interleavings lead to the same result. Partial-order semantics allow the unordering of independent events of concurrent processes. Completeness remains, and the required computation drops by 60 to 80 percent.

5.3 Finite State Machines methods

The theory of Finite State Machines (FSMs) is a vast theory, which revives today with the problem of testing communication protocols. Their study brings methods that can substitute brute-force methods when trying to prove formally something on a huge amount of states.

5.3.1 Definitions

5.3.1.1 Finite State Machines

A *Finite State Machine* is a set of states linked by transitions governed by a transition function, with an input and an output. There are two kinds of FSMs: Mealy and Moore machines. The only difference is that for a Moore machine, each time a different output is given, the other parameters being identical, we have another state, whereas in the Mealy Machine, the output is given in transitions from one state to the other. Then, a Moore machine is clearer but a Mealy machine has

much fewer states. Because we know we have to face a state explosion, Mealy machines will be used.

A *Mealy machine M* is a quintuple *(I, O, S, δ, λ),* where *I*, *O* and *S* are finite, non-empty sets of input symbols, output symbols and states, respectively.

δ: SxI → S is the transition function,

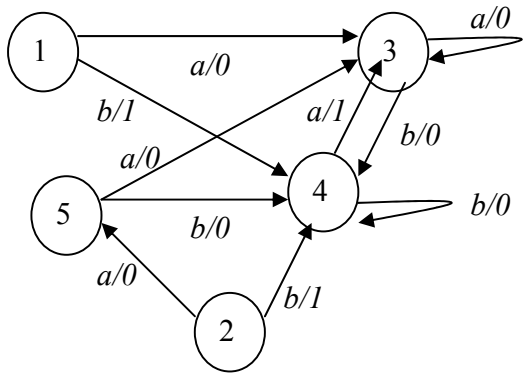
λ: SxI → O is the output function.

A transition between two states is usually represented as an arrow, with the comment input/output near to it. It links two states, represented as circles.

The meaning of δ and λ is extended, so that the input can be a list of input variables, taken one after the other, and so that the output is the concatenation of the successive outputs when we go through the FSM.

Two states *S* and *S'* are said to be *equivalent* if and only if, for a machine of N states:

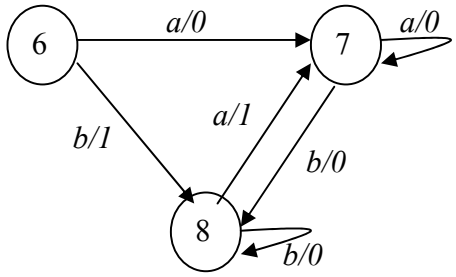
∀ x input sequence, λ(S,x)= λ(S',x)



- Here, states 1 and 2 are equivalent. If the input begins with a *b*, both states will output 1 and lead to state 4. If the input begins with a *a*, both states will output 0 and lead to states 3 or 5. So 1 and 2 will be equivalent if and only if 3 and 5 are equivalent. For states 3 and 5, an input *a* will give output 0 and lead to state 3; an input *b* will give output 1 and lead to state 4. So 3 and 5 are equivalent, and thus, so are 1 and 2.

Two machines M and M' are equivalent if and only if:

∀ S state of M, ∃ S' state of M' so that S and S' are equivalent.



- Quite simply, it was possible to create a machine that is equivalent to the previously drawn machine. State 6 is equivalent to states 1 and 2; state 7 is equivalent to states 3 and 5; state 8 is equivalent to 4.

Let $M=(I, O, S, \delta, \lambda)$ and $M'=(I, O, S', \delta', \lambda')$ be two FSMs with the same input and output. We say ϕ is a *homeomorphism* (or *morphism*) from M to M' if and only if:
$\forall s \in S, \ \forall a \in I, \delta'(\phi(s),a)= \phi(\delta(s,a))$ and $\lambda'(\phi(s),a)= \lambda(s,a)$
If ϕ is a bijection, then it is called an isomorphism, and M and M' are isomorphic. Two isomorphic machines are also equivalent, but it is not reciprocal.

- Counter-example: we saw that the two machines described upper are equivalent. But they are not isomorphic: it it were the case, the isomorphism being also a bijection, the number of states in both machines would be the same.

From each machine, we can construct an *equivalent minimized machine*, which will have the minimal possible number of states. To do this, we group states that have the same behavior (same inputs, same outputs…).

5.3.1.2 Testing a FSM

We now have a finite state machine that represents what we want to test. So, what and how are we going to test it?

Usually, concerning a machine M, four fundamental questions are raised:
1 What will the final state be after we have run a given test?
2 What is the initial state of the machine, and how to verify it?
3 If we are given a specification, is M equivalent to the specification machine?
4 What does machine M do?

The first two problems are more generic. Between the last two, the third question corresponds most to the aim of the tests I have done at Motorola. So it will be developed more, and the last point will be neglected.

To get answers to these questions, we need to perform tests. A test may be *preset* or *adaptive*.
A preset test is a test where the input sequence is fixed at the beginning and does not change.
An adaptive test is a test where the input changes according to the previously observed outputs. It has a tree structure.

For the tests, what is used is only a list of messages that have to be checked or sent, which corresponds to preset tests. So, adaptive tests will not be developed further.

5.3.1.3 Particular sequences

For a reduced machine, a *homing sequence* is a sequence of inputs, for which, whatever the starting state, we know in which state the machine is after the input is applied.

It is possible to build such a sequence easily. We take two arbitrary states in the machine, and find an input which separates them. Then, we apply this input to all possible states, and sort the states by groups of specific outputs. Recursively, we choose a new input, and apply it to each of the groups, to obtain smaller subgroups, until the groups are nothing more than singletons. The succession of inputs applied is then a homing sequence.

Still for a reduced machine, a *synchronization sequence* is a sequence that takes the machine to the same final state, regardless of the initial state. All machines do not have a synchronization sequence. A synchronization sequence is a particular homing sequence.

Using homing sequences, we can already answer the first question, which was to know the final state of the machine.

5.3.2 State identification and verification

State identification and *state verification* are two problems that seem to be very near, but whose possible solutions are quite different.

State identification consists in finding the initial state of a machine, knowing its complete state diagram. A *distinguishing sequence* is a sequence of inputs that solves this problem. All machines do not have a distinguishing sequence. A distinguishing sequence is also a homing sequence.

State verification consists in checking that the machine has the initial state it is supposed to have. A *UIO* (Unique Input-Output) *sequence* is a solution to this problem. If a machine has a distinguishing sequence, then all the states of this machine have a UIO sequence.

Unfortunately, algorithms to find distinguishing sequences often have an exponential complexity for preset tests.

5.3.3 Conformance testing

We know turn to question three, i.e. to know if a given machine is equivalent to the specification machine.

To be able to test the equivalence between a specification machine A and an "implementation machine" B, we need several hypotheses which are:

- A is strongly connected, which means it is possible to reach any state, starting in any state,
- A is reduced,
- B does not change during the experiment and has the same input alphabet as A,
- The number of states of B is less than or equal to the number of states of A.

Let us first introduce a few new definitions that are going to be required.

Let $M=(I, O, S, \delta, \lambda)$ be a FSM. A separating family of sequences for machine M is a set of n sets of input sequences Z_i, $i=1..n$, where n is the number of states, such that:
$\forall (s_1,s_2) \in S^2, \exists (j,k) \in [1..Card(Z_1)]x[1..Card(Z_2)], \exists \alpha$ *prefix of* Z_{1j} *and* Z_{2k}, *such that* $\lambda(s_1,\alpha) \neq \lambda(s_2,\alpha)$ (*)

Let $M=(I, O, S, \delta, \lambda)$ and $M=(I', O', S', \delta', \lambda')$ be two FSMs.
A state $s \in S$ with a separating set Z is said to be similar to a state $s' \in S'$ with a separating set Z' if and only if:
$\forall i \in [1..Card(Z')], \lambda(s,Z'_i) = \lambda'(s',Z'_i)$
The machine M will be similar to machine M' if and only if :
$\forall s \in S, \exists s' \in S'$, *such that s is similar to s'*

To compare two machines, we must also be able to see the status messages of all states, that is to be able to identify the state in which we are. In protocol testing, this is possible, since we can observe the values of the variables, the set of all variable values characterizing a particular state. So this hypothesis is always verified.

A status message is said to be reliable if it outputs the current state without changing it. As it is the case (a watchpoint on a variable does not modify it), we can check the correct functioning of B by constructing a covering path of A, and applying the status message at each state visited.

It is easier to build a verifying sequence if the machine A has a reliable *reset* capability. Such a capability exists if and only if:
$\exists r \in I, \forall s \in S, \delta_A(s,r)=s_0$, s_0 being the initial state

Using this reset capability, it is possible to build easily a test sequence testing all the states, by coming back to the initial state after each test is performed. This leads to polynomial-time algorithms.

Here is an example of such an algorithm, using the previous similarity definition. It is made of two steps:

- Similarity testing
- Isomorphism testing

We use the FSMs $Imp=(I, O, S, \delta, \lambda)$ and $Spec=(I', O', S', \delta', \lambda')$, and we want to test the conformance of the implementation machine *Imp*, given the specifications machine *Spec*.

Similarity testing

To check that *Imp* is similar to *Spec*, we have to test the similarity for each state of *Imp*. Let us test a given state $s' \in S'$.
We apply a synchronization sequence of s' in machine *Imp*. Such a sequence exists since we have the properties of strong connection and of existence of reliable reset capability.
We should now be in the state $s \in S$ we want to prove is similar to s'. We apply all separating sequences of s' to s. If the outputs are the same, s is similar to s'.

Isomorphism testing

The beginning is the same: we apply a synchronization sequence to reach a given state $s' \in S'$ (all have to be checked again). We obtain state $s \in S$ in the *Imp* FSM.
For every possible transition from *s'* in *Spec*, we apply the same input to state *s*. We then apply a separating sequence of *s',* to the state reached in *Imp*. If separating sequences outputs for all transitions give the same results as in the *Spec* machine, we know that *Imp* is isomorphic to *Spec:* the conformance is proven.

Complexity calculus

Let *n* be the number of states in *M'*. For similarity testing, we need to check the similarity to these *n* states. For each test, a homing sequence is applied, of length at most *n*. *S'* has at most *n* separating sequences, of length at most *n* for each. So the complexity is polynomial as it is (probably less than) $O(n^3)$. The isomorphism testing complexity gives the same result.

There are other algorithms to check the conformance, for example:

- Using distinguishing sequences, the algorithm goes through all of the states successively (there is always a path from one state to the other since the machine is strongly connected), and applies distinguishing sequences to all states.
- Using identifying sequences, which identify a state in the middle of the execution. The conformance is tested by analyzing the response of all states to given sets of sequences called separating sets.

(*) For simplification reasons it is assumed Z_1 and Z_2 are the sets corresponding to S_1 and S_2 respectively. A more rigorous notation would be Z_{i1} and Z_{i2}

5.3.4 FSMs in the reality

For the testing of the implementation of the EAB feature, FSMs can be used. But the complexity of GSM ensures that the number of states of the specification machine is huge! Furthermore, what we want to test is not the exact conformance to the specifications. As a matter of fact, a specification cannot be perfect, and it may contain errors that we do not want to be translated in the code. So, both the specification and the implementations machines evolve at the same speed.

But some theoretic aspects still need to be kept and used. If we want to test correctly according to the specification we have, we should refer to the third problem evoked upper, and use one of the possible methods that have been presented.

In our case, a reliable reset capability exists, using the STEP simulator. It is indeed always possible to come back to the same initial state using it, where default files are read before the beginning of any test. The corresponding method would then seem to fit most, but is impossible to apply today because of the lack of theoretical formalities in the telecommunications field.

6 Testing the EAB

6.1 Description of the test tool: STEP

STEP stands for *Simulator Tool for Early Protocol*. It is a tool developed by Motorola Toulouse, to be able to perform tests on the low protocol layers, inside a controlled simulated environment.

STEP provides different possible environments: different platforms but also different levels of protocol. During my master thesis for example, the RR/L1 and the MM/RR/L1 simulators were used.

The following scheme shows what environment STEP simulates, where the official code intervenes, and on which parts STEP scripts have an effect.

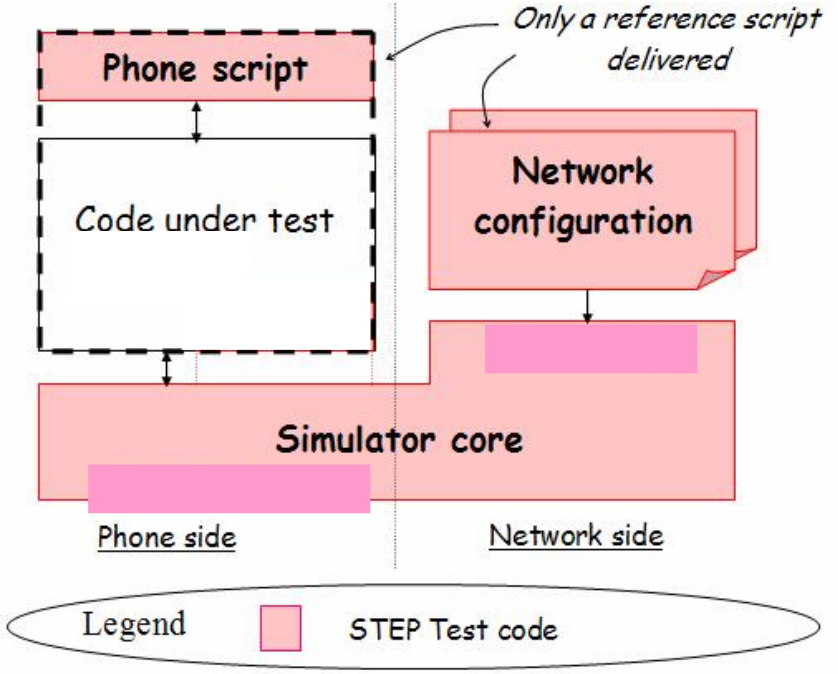


Figure 3: What STEP does and does not

Let us take the example of a RR/L1 simulator. The "level of the script" is RR. So, the lower layers (L1 here) will correspond to what exists in the official code. The parts provided by STEP will be what happens below L1, i.e. near-to-electronics tasks, and radio environment simulation.

It will also simulate other parts, but this will depend on what the user asked in the scripts. The sent messages at the reference protocol level are contained in the main script, as well as the messages that are expected in response from the lower layers. Other auxiliary scripts describe the

various settings of the phone, and the configuration of the network (are there available PLMNs, what are the powers of the present cells, and so on).

6.2 The main groups of tests

To try to cover as many cases as possible, the possible tests were sorted in some big groups of test circumstances. Let us now see what they are.

6.2.1 Power-up with SIM

The MS is powered-up, and a valid SIM card is inserted. This group contains 23 tests.

6.2.2 Power-up without SIM

The MS is powered-up without SIM card, and can only camp in emergency. This group contains 6 tests.

6.2.3 Loss of camp

The MS loses the coverage corresponding to the PLMN it was registered on. This group contains 22 tests.

6.2.4 Network registration failures

After the MS has tried a few times to do a network registration on its camped PLMN, it enters a special state, where it tries to camp on another PLMN. This group contains 20 tests.

6.2.5 Periodic HPLMN search

Every $6N^{th}$ minute, where N is an integer, the MS tries to find and camp on the home PLMN. This group contains 8 tests.

6.2.6 Manual network search

The user may request the phone to display the list of available PLMNs. This group contains 8 tests.

6.2.7 New network search

The user may request the phone to camp on a new PLMN, i.e. a PLMN different from the RPLMN. This group contains 12 tests.

6.2.8 Cellar Effect

MS enters a cellar effect mode when

- no coverage is found,
- emergency camped.

This case groups all the cellar effects that can be reached in the other groups, and examines how the MS exits this mode. This group contains 8 tests.

6.3 The varying parameters

Many parameters can lead to totally different expected results in the tests. Here is a list of the parameters that were made vary to cover as many cases as possible.

6.3.1 Automatic vs. manual network selection

In automatic mode, the user does not need to care about the choice of PLMN. The MS chooses by itself the best PLMN. To choose this best PLMN, the ETSI specifications give priorities to the different kinds of PLMNs that can be chosen:

1 The RPLMN has top priority, the exception being the periodic HPLMN search, where the HPLMN has highest priority,
2 The HPLMN has second highest priority,
3 If a list of preferred PLMNs is defined, and neither the RPLMN nor the HPLMN are there, preferred PLMNs have priority. PPLMNs are a ranked list chosen by the user,
4 If none of the above are available, a random PLMN whose power is greater than -85 dB is chosen.
5 If no PLMN is powerful enough, the most powerful one is chosen.

The automatic mode is usually the one chosen.

In manual mode, a list of PLMNs is displayed to the user and he/she chooses the PLMN on which he/she wants to camp. A new PLMN list is displayed as soon as the choice is not obvious: when the RPLMN is no longer available.

6.3.2 Autoband vs. chosen band

In the network options, the user may choose to be in autoband or he/she may prefer to choose a fixed frequency band on which to work. This can be interesting for a user staying in a European country, where he/she is certain 850 and 1900 bands will not be necessary.

The effects of Autoband were described in sections 4.2 and 4.3.

The tests had to cover the Autoband functionality, but some of them covered the cases where the band is constant as well, to check there were no regression effects.

6.3.3 Phone capability

There are lots of possible phone capabilities, associating in different ways the following frequency bands: 900, 1800, 850 and 1900.

Here is a table listing all the possibilities for the phone capability.

Kind of capability	European bands	American bands
Monoband Europe	900	-
Monoband Europe	1800	-
Bi-band Europe	900/1800	-
Monoband US	-	850
Bi-band Europe/US	900	850
Bi-band Europe/US	1800	850
Triband	900/1800	850
Monoband US	-	1900
Bi-band Europe/US	900	1900
Bi-band Europe/US	1800	1900
Triband	900/1800	1900
Bi-band US	-	850/1900
Triband	900	850/1900
Triband	1800	850/1900
Quadband	900/1800	850/1900

Figure 4: possible phone capabilities

Even if most of phones nowadays are quad-band, it is useful to check if EAB works as well for rarer capabilities.

6.3.4 Last band selected and RPLMN

Another parameter is the last band on which the MS was.

This parameter goes by pair with the number of the PLMN we were last camped on.

6.3.5 Other specific PLMNs

Among the possible parameters, we should also set:

- The value of the HPLMN,
- The values of the FPLMNs, if there are some,
- The values of the PPLMNs, if there are some.

6.3.6 The radio environment

It would be useless to define what the phone's preferred PLMNs are if we cannot control the available cells in the phone environment!

It is possible to define the ARFCNs of all cells that are present, as well as their power and corresponding PLMN.

6.3.7 EAB Algorithm initialization parameters

Last of all, some elements may look trifling, as they only correspond to a single Boolean value, but they can change greatly the behavior of the EAB algorithm. Those parameters are used to optimize the algorithm performance depending on circumstances. Note that if those elements are not set properly the phone behavior can be erratic or non-optimized.

6.4 Tests procedures

6.4.1 Feature Complexity and test coverage

Let us do simple, approximate calculus to try to evaluate the number of possible tests. Let us multiply:

- 2 modes of network selection (automatic and manual)
- 2 modes of band selection (automatic and manual)
- 15 phone capabilities
- 2 possible lastly selected bands (belonging to 900/1800 or 850/1900)
- 10 typical RPLMN/HPLMN/PPLMN/FLMN configurations
- 10 typical radio environments
- 2x2x2 values for the main three initialization parameters.

Testing absolutely all the cases would amount to 96000 tests!
This is why the most relevant 1‰ sample of these tests was chosen.

To cover as many cases as possible, let us split tests into subgroups inside the big behavior groups. These subgroups corresponded to the possible network coverages on the different bands:

- No coverage at all,
- Coverage only on currently selected band(s),
- Coverage only on currently not selected band(s),
- Coverage on both bands.

For some groups of tests where that was relevant, coverages including forbidden PLMNs were added:

- Only FPLMNs on current band(s), and nothing better (no coverage nor FPLMNs) elsewhere,
- Only FPLMNs on current band(s), and normal coverage elsewhere,
- No coverage on current band(s), and only FPLMNs elsewhere.

In each of these subgroups, four cells(*) were created, corresponding to the choice between automatic and manual network and band selections. For some special behavior groups, the influence of an initialization parameter raised the number of cells to six.

Concerning the phone capability, five typical configurations were chosen:

- 1800 for a mono-band phone,
- 850/1900 for a “normal” dual-band phone,
- 900-1900 for a dual-band phone with a band on each knife switch mode,
- 900/1800-850 for a tri-band phone,
- 900/1800-850/1900, which is the quad-band capability.

These five values were then dispatched among all the cells.

Finally, only a choice between the most relevant cells was done, to limit the number of tests. For example, in a subgroup like this:

1 – Manual network selection, Manual band selection	2 – Manual network selection, Automatic band selection
3 – Automatic network selection, Manual band selection	4 – Automatic network selection, Automatic band selection

The implementation of tests 1 and 3, or tests 2 and 4, was chosen, to have the largest variety.

Once this was done, the tests only needed further specifying, like for example detailing the presence of the RPLMN, the availability of the HPLMN or the existence of PPLMNs.

At the end, I got 107 tests, the number of tests in each behavior group being specified upper in 6.2.

** In this paragraph, I speak of array cells, not to confound with cells of the radio environment*

6.4.2 Three scripts, one test

After all the tests were formally specified and accepted, the remaining task was the implementation under STEP.

A STEP test needs four scripts:

- One main script specifying the names of the other needed scripts, as for a *#include*. This script also tells the messages that are sent by the simulated highest layer of protocol, as well as the expected answers from the lower layers.
- One script to specify MS settings such as the HPLMN, RPLMN, FPLMNs and PPLMNs.
- Two scripts to specify the radio environment.

The first simulator that was used was a RR/L1 simulator. But it was not efficient enough, since half of the tests could only be implemented at MM level, and for the others, some aspects were not tested. However, the implementation of 50 RR tests provided the required training with STEP before tackling the writing of the MM tests.

6.4.3 Outlook of a STEP test

Let us now see what a STEP main script looks like:

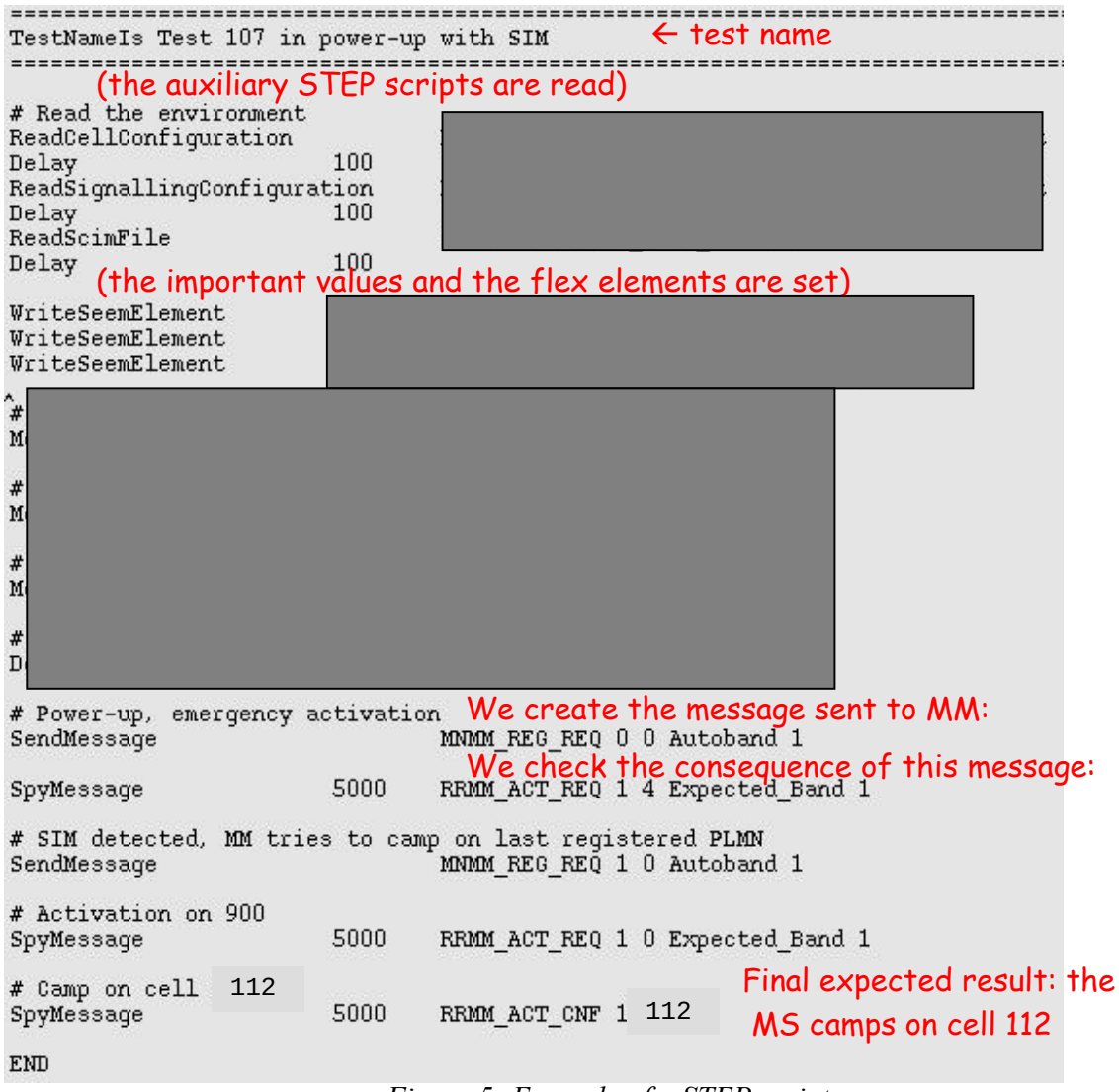

TestNameIs Test 107 in power-up with SIM
← test name
(the auxiliary STEP scripts are read)
Read the environment
ReadCellConfiguration
Delay 100
ReadSignallingConfiguration
Delay 100
ReadScimFile
Delay 100
(the important values and the flex elements are set)
WriteSeemElement
WriteSeemElement
WriteSeemElement
Power-up, emergency activation
We create the message sent to MM:
SendMessage MNMM_REG_REQ 0 0 Autoband 1
We check the consequence of this message:
SpyMessage 5000 RRMM_ACT_REQ 1 4 Expected_Band 1
SIM detected, MM tries to camp on last registered PLMN
SendMessage MNMM_REG_REQ 1 0 Autoband 1
Activation on 900
SpyMessage 5000 RRMM_ACT_REQ 1 0 Expected_Band 1
Camp on cell 112
SpyMessage 5000 RRMM_ACT_CNF 1 112
Final expected result: the MS camps on cell 112
END

Figure 5: Example of a STEP script

What this scripts test can be summarized with the following scheme of messages sent and received:

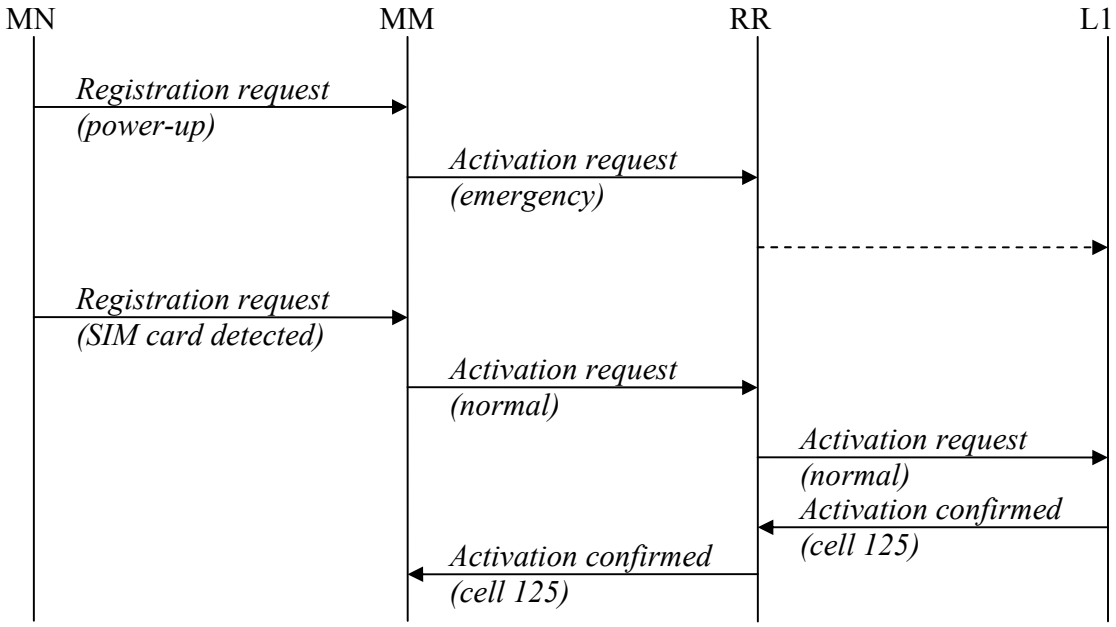


Figure 6: Messages transmitted between the protocol layers

Messages in italics are the only ones tested in the script.

The MN layer (all that is necessary to know is that it is a layer on top of MM) sends a registration request on power-up. We only check that this is followed by an emergency activation request sent by MM to RR. We do not check the following, and immediately send another registration request, because the SIM card has been detected. The consequence is a new activation request, sent by MM to RR, asking RR to camp on the RPLMN if it finds it. RR relays this message to L1. L1 finds the RPLMN, and camps on it. L1 sends a confirmation of that to RR. RR relays this confirmation to MM, this last message being the last thing tested in the script.

6.5 Tests results

The writing of the tests was very profitable.

- They helped improve the STEP tool, adding new possibilities that were required for some tests,
- Some bugs appeared and were corrected thanks to these tests,
- The 107 tests can now be run in a row, to check in the future that improvements of the code will not affect the correct functioning of the EAB feature.

7 Conclusions and further work

From a personal development point of view, the twenty weeks spent at Motorola were very profitable:

- Many details of the PLMN selection process in the EAB could be learnt,
- The possibility was given to think, try to understand, and resolve when needed, the issues raised by these scripts, directly on Motorola's stack code,
- The possibility was given, to work and exchange ideas inside a motivating team, always ready to answer questions and discuss problems.

There are two main directions in which to continue the work and improve one's knowledge.

In the telecommunications field, GSM is a small part and EAB even a much smaller one! Many concepts are linked in this area, and trying to develop one's knowledge about a specific aspect inevitably leads to the understanding of other definitions and processes. For EAB alone, some information can be found on various fields such as:

- the consequences of EAB on the upper layers,
- the details of the cellar effect when no coverage is found,
- the possible behavior differences when EAB works with GPRS…

Concerning theoretical testing, for example with FSMs, it is still not much used in the industry nowadays. The problem comes from the amount of states in a communication protocol, which makes it difficult to use such methods without having an exaggerated time complexity. There is still some research to be done to discover a simpler method, with a quick and efficient algorithm that would be proven to test say 99.9% of possible states for conformance with the specification machine.

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